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LUNAR STORAGE OF LIQUID PROPELLANTS

By W. E. Dempster, R. L. Evans, and J. R. Olivier

George C. Marshall Space Flight Center
Huntsville, Alabama

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SUMMARY

The thermal environment of liquid propellant storage tanks located on the lunar surface and subsurface was investigated. The surface temperature of storage tanks located on the lunar surface depends upon the rates at which solar energy, infrared, and albedo are absorbed and reradiated by the tank. A method for artificially altering the local lunar surface temperature and the surface temperature of a tank is introduced.

The surface temperature of a tank located beneath the lunar surface is established by the lunar subsurface temperature.

The heat flux of two geometrically similar tanks containing LH_2, one located on the lunar surface at the Equator, and the other buried, can be made nearly equal.

From a thermal standpoint it is concluded that storage of any liquid propellant on the moon is possible with present day materials and technology.

SECTION I. INTRODUCTION

Lunar storage of liquid propellants for space vehicles either off or onboard requires an investigation of lunar environmental conditions and their influence on storage tank design. Environmental conditions such as cosmic irradiation, ultraviolet irradiation, gravitational field, meteorite density, thermal radiation, etc., must be considered. This report, however, is limited to an investigation of the thermal design conditions which are determined principally by the laws and mechanisms of radiant heat transfer.

The lunar surface is described as a very good insulator ($k = 10^{-4}$ cal/cm-sec$^{\circ}$C at or near the surface) with properties quite similar to those of a black body. For these reasons the lunar surface undergoes severe temperature fluctuations (day 393°K maximum; night 143°K minimum) while its subsurface temperature is nearly constant (233°K a few centimeters below the surface).

Three sources of radiant thermal energy establish the thermal environment of a liquid propellant storage tank situated on the lunar surface; they are: direct solar, lunar albedo, and infrared.

Direct solar energy with an average intensity of 0.0316 cal-sec^{-1}-cm^{-2} will irradiate the storage tank during the lunar daylight period. Proper selection of the tank's surface properties must be made to reflect the majority of this thermal energy.

Albedo is solar energy which is scattered and reflected from the lunar surface and has an intensity of approximately seven percent of the direct solar energy. Storage tank surface properties required to reflect albedo are the same as those required to reflect direct solar energy.

Infrared is radiation emitted from the lunar surface and is directly proportional to the fourth power of the absolute temperature of the lunar surface.

The thermal environment of a storage tank buried beneath the lunar surface is established by the subsurface temperature and the thermal conductivity and thermal diffusivity of the subsurface material.

The report, although preliminary in scope, indicates the magnitude of the thermal environment of liquid propellant storage facilities located on the lunar surface and subsurface. Several tank configurations are examined for above-ground storage, and a concept which would reduce the lunar surface temperature and tank surface temperature is introduced (FIGURE 1).

SECTION II. BASIC ASSUMPTIONS

The following simplifying assumptions were made to expedite this investigation:

1. During the lunar daylight period, the absolute temperature of the lunar surface is expressed as a function of the time angel τ, and the latitude angle β .

2. The ecliptic plane and the lunar equatorial plane are coplanar.

3. The storage tank is assumed to be perfectly insulated to permit the skin temperature of the tank to be evaluated.

4. The outer skin of the storage tank has an infinite thermal conductivity in a direction orthogonal to the flow of heat tending to enter or leave the propellant; hence, the surface temperature of the storage tank is uniform at any given time angle τ .

5. Secondary reflections of radiant thermal energy are negligible.

6. The storage tank is located on an infinite plane.

SECTION III. DISCUSSION OF ASSUMPTIONS

1. The absolute temperature of the lunar surface can be expressed as a function of the time angle τ , and the latitude angle β , by ignoring local topographical variations and treating the moon as a perfect sphere. Many maria and planes of the moon closely approach this condition.

2. The ecliptic plane and the lunar equatorial plane are inclined 1° 32' with respect to each other, and thus are nearly coplanar.

3. The ideal or perfect insulation is approached by presently available superinsulations (e.g., Linde SI 62) which have an extremely low thermal conductivity and only permit the passage of small amounts of heat per unit time.

4. Considerable variations of temperature will exist on the storage tank surface; however, it was felt that an average temperature would provide a representative temperature of the tank surface as a function of time and latitude. The error introduced by this assumption produces slightly optimistic results with respect to the amount of heat entering or leaving the propellant as calculated in Section V, i.e., more heat actually enters or leaves the propellant.

5. Investigations conducted during the course of this study showed the resultant effects of secondary reflection in the infrared region to be relatively insignificant for low α/ϵ surface properties.

6. The error introduced as a consequence of considering the lunar surface within the storage tank's horizon to be an infinite plane is negligible if the tank is assumed to be located on level ground and away from any large mountains.

SECTION IV. THERMAL ENVIRONMENT OF ABOVE-GROUND STORAGE TANKS

The thermal environment of liquid propellant storage tanks located on the lunar surface is principally dependent on radiative heat transfer and, to a lesser degree, on heat transfer by convection and conduction.

Radiation received by the tank is determined by a balance of the heat flow from all heat sources and sinks. One such source is the moon itself which emits infrared energy in direct proportion to the fourth power of its absolute temperature. FIGURE 2 presents a graphical representation of the lunar surface temperature as a trigonometric function of the latitude location angle β and its location with respect to the sun in terms of a time angle τ (Appendix B). This graph shows that the lunar surface temperature is independent of latitude location during the lunar night period, at which time its temperature is a minimum (143°K). During the lunar day period, however, the lunar surface temperature depends on the latitude location and time location, i.e., the temperature increases as the sun's rays become more nearly perpendicular to the area under consideration.

Since the temperature of the moon's surface is a measure of its ability to emit radiation, it was conceived that some control of the emission rate could be had if the lunar surface was artificially altered. For this purpose it was proposed that a layer of powder material with suitable radiation properties be spread on the area under consideration. FIGURE 3 presents a graphical illustration of the results which could be obtained by covering a limited area of the lunar surface with titanium oxide, TiO_2, powder (α/ϵ = 0.2). It should be noted here that the lunar surface temperature during the day period is considerably less than the corresponding temperatures of the uncovered lunar surface shown in FIGURE 2. The surface temperature during the night period is approximately the same, since the infrared emissivity of the moon and TiO_2 are nearly the same. Thus, it may be projected that the lunar surface temperature and, consequently, the emission rate of infrared radiation from the lunar surface to the tank may be controlled locally by proper selection of the spread powder.

The surface temperature of a tank located on the lunar surface may be expected to vary in a manner similar to the lunar surface. FIGURE 4 presents a surface temperature history during an entire lunar cycle for a spherical storage tank coated with TiO_2 at various latitude locations on the moon. It is seen that the surface temperature of the tank is considerably lower than the unaltered moon surface temperature as shown in FIGURE 2 throughout the majority of a complete lunar cycle. The surface temperature history of a spherical tank on the moon's equator for various tank surface coatings (α/ϵ ranges from 0.2 to 4.43) is presented in FIGURE 5.

FIGURE 6 shows the temperature history of a spherical tank coated with TiO_2 located on the lunar equator (β = 0), and centrally situated with respect to various size circular areas of the lunar surface which have been altered with TiO_2 powder. A similar graphical representation of the tank situated within circular powder-covered areas for other lunar latitude locations is shown in FIGURES 7, 8, 9, 10, and 11. It should be noted that the tank surface temperature is below that given in FIGURE 4 during the daylight period for respective latitude locations.

Tank geometry and the resultant effect on tank surface temperature was also examined. FIGURE 12 presents the temperature history of a shrouded spherical tank, TiO_2 coated (FIGURE 1.), for various lunar latitudes. Comparison of corresponding latitude temperatures of this graph with FIGURE 4 shows that the shrouded tank surface temperature is below that of the spherical tank.

Thus, one might reasonably expect that a suitable tank surface temperature history may be obtained for a given latitude location by:

1. Proper selection of the tank's surface properties.

2. Spreading of an appropriate powder in the vicinity of the storage tank.

3. Control of the storage tank geometry.

SECTION V. HEAT FLUX TO LIQUID PROPELLANTS STORED ON THE LUNAR SURFACE

The time period a liquid propellant can be stored on the lunar surface without appreciable boiloff or density change is dependent upon the net total heat flux received or rejected during the storage period. For a given equilibrium propellant temperature, type of insulation, and insulation thickness, the Fourier heat conduction equation shows that the instantaneous heat flux is dependent upon the tank surface temperature and may be positive, negative, or zero, i.e., the propellant may receive heat, reject heat, or remain in thermal equilibrium. However, it should be noted that the instantaneous heat flux determined may not be felt by the propellant immediately, due to the thermal lag of the insulation. The net total heat flux received or rejected is determined by integration of the Fourier equation over the entire storage period. Since this integration is in reality a summation of the instantaneous heat fluxes, it is easily seen that the surface temperature history of the tank determines if the net total heat flux with respect to a given propellant is positive, negative, or zero.

A. LOW BOILING POINT PROPELLANT

The cryogenic family of propellants exhibit phase equilibrium temperatures which are considerably lower than the tank surface temperatures obtainable at any lunar latitude. For this reason, the net total heat flux of a cryogenic storage tank is positive throughout all phases of a complete lunar cycle. However, since the tank surface temperature influences the magnitude of this heat flux, some remarks pertaining to those properties which influence the tank surface temperature are in order.

The surface properties of a cryogenic storage tank should have a minimum α/ϵ ratio to reflect the majority of incoming solar radiation and emit the greatest amount of infrared radiation. Titanium oxide, for example, is commercially available and has an α/ϵ ratio which is reasonably low (on the order of 0.2). TiO_2 withstands ultraviolet radiation without deleterious effects.

As has been indicated in the previous section, the lunar surface might be altered to control the tank surface temperature. If this is practical, it would be desirable to spread a powder with a low α/ϵ ratio. Titanium oxide is suggested.

The tank configuration selected should produce the minimum geometrical shape factor with respect to the moon surface and the sun. This may not be practical or possible due to other considerations. For example, the tank shape which could most easily be launched from the earth to the moon might have a shape factor considerably higher than another configuration. In this instance, the orientation of the tank with respect to the moon surface and solar source should be considered and evaluated very carefully.

Latitude location on the lunar surface is also an important consideration from a thermal standpoint. It would be desirable to locate a cryogenic storage tank at an elevated latitude on the lunar surface. This consideration, however, is secondary, since the latitude location will be dictated by the landing site selected and the area to be investigated and explored.

B. HIGH BOILING POINT PROPELLANTS

The equilibrium temperature of high boiling point fuels falls within the range of temperatures a tank configuration is subjected to during the course of a lunar cycle at a given latitude. Thus, it may be postulated that the fuel may be kept at or near a constant temperature by proper selection of geometry and surface properties, lunar surface properties, latitude location, and insulation. Due to the lack of information concerning the thermal properties of high temperature insulation subjected to vacuum conditions, an analysis of this storage problem was not possible. However, some preliminary comments may be made. Generally speaking, the tank should be located at a relatively low lunar latitude, and have a geometrical configuration which produces large shape factors with respect to the sun and the moon. In addition, solar energy must be incident upon the tank and moon during a part of the storage period to ensure that the propellant receives as much heat during one phase of its storage as it loses in another phase to remain in thermal equilibrium. Short term storage of this class of propellants will require additional considerations relating to the storage time period.

SECTION VIII. CONCLUSIONS

The surface temperature of a well insulated liquid propellant storage tank situated on the lunar surface is not necessarily equal to the lunar surface temperature. This report shows that the direct solar irradiation, albedo, and infrared received by such a tank and, hence, the storage period of liquid propellants on the lunar surface, are dependent upon the surface properties of the tank.

The type of propellant (low or high boiling point liquids) exercises considerable influence in the determination of the tank's surface properties, geometry, and latitude location which will permit an above-ground storage tank to be insulated with the least amount of material. Table I summarizes these variables for low and high boiling point propellants, and includes the altered lunar surface properties which would be conducive to storage of these fuels:

TABLE I

	Low Boiling Point (Propellant)	High Boiling Point (Propellant)
Surface Properties	Low α/ϵ ratio (0.2-0.3)	High α/ϵ ratio (1.0-4.0)
Tank Geometry	Small shape factor with respect to the moon surface and incoming solar irradiation	Large shape factor with respect to the moon surface and incoming solar irradiation
Lunar Latitude Location	Upper latitude	Lower latitude
Altered Lunar Surface Characteristics	Low α/ϵ ratio (0.2-0.3)	High α/ϵ ratio (1.0-4.0)

The storage period of a tank located beneath the lunar surface is dependent upon the lunar subsurface temperature and subsurface properties.

In conclusion, a comparison (Appendix D) of two geometrically similar storage tanks containing a low boiling point propellant (LH_2), one of which is located on the lunar surface at the equator, and the other buried, indicates that with proper surface properties, the heat fluxes can be made nearly equal. It is shown in Appendix E that 13,600 kilograms of LH_2 may be stored for approximately six months with only a 10 percent loss of propellant by venting. Therefore, factors other than heat transfer would determine if it is more conducive to store above-ground or below. High boiling point fuels, on the other hand, have a decided thermal advantage in being located on the lunar surface, since it would be possible to store them indefinitely without any serious change

SECTION VI. THERMAL ENVIRONMENT OF BELOW-GROUND STORAGE TANKS

A liquid propellant storage tank buried beneath the lunar surface has a skin temperature which is equal to the temperature of the lunar material in contact with the tank. The temperature of this subsurface material is initially dependent upon the time of burial and the method of burial. It is readily understandable that the time of burial plays a considerable role in establishing the temperature of the subsurface material if one considers that the temperature of the fill material is considerably higher during the lunar daylight period than it is during the night period. The burial method also plays a role in determining the temperature of the fill material, for if the fill material is a mixture of surface and subsurface materials, a combination of temperatures is involved.

Since the temperature of the liquid propellant and the lunar contact material are more than likely at temperatures different from the lunar subsurface temperature, a transient period will occur after burial, during which time the tank surface temperature will tend to approach equilibrium. The time duration of this period will be established by the heat leak to or from the tank and the thermal diffusivity of the lunar subsurface material.

Because of the complexity of this problem, the tank surface was assumed to be equal to the temperature of the lunar subsurface, i.e., $233^{\circ}K$.

SECTION VII. HEAT FLUX TO LIQUID PROPELLANTS BENEATH THE LUNAR SURFACE

As was the case for above-ground storage, the time period a liquid propellant can be stored below the lunar surface without appreciable boiloff or density change is dependent upon the total heat flux received or emitted during the storage period.

The assumption that the tank surface temperature is the same as the lunar subsurface temperature provides a conservative estimate of the steady state heat flux for the storage period. In reality, if the stored propellant has an equilibrium temperature higher than lunar subsurface, the surface temperature of the tank would be above the average lunar subsurface temperature; therefore, the propellant would emit less heat than that which is calculated. In the same way, a propellant stored with an equilibrium temperature lower than the lunar subsurface temperature would actually receive less heat than that calculated.

It should be noted here that it is not possible to store either the low boiling point or high boiling point propellants and have them remain in equilibrium as was the case for above-ground storage of high boiling point propellants. This is easily understood, since the equilibrium temperature of these propellants is either above or below the lunar subsurface temperature. Thus, below-ground storage of liquid propellants can be for a finite period only.

APPENDIX A

SYMBOLS

A	-	Area, square meters
S	-	Solar constant at 1AU, 0.0316 Cal-Sec^{-1}-Cm^{-2} or distance between two radiating surfaces, meters
σ	-	Stephan Boltzman constant, 1.37X10^{-12} Cal-Sec^{-1}Cm^{-2}-K^{-4}
α	-	Absorptivity
θ	-	Angle, degrees
γ	-	Angle, degrees
β	-	Latitude angle, degrees, or an angle formed by normal to radiating surface and line representing the distance S
τ	-	Time or time angle
ρ	-	Reflectivity
C	-	Heat capacity, calories-total grams^{-1}-oK^{-1}
T	-	Temperature, °K
φ	-	Sun rays angle, degrees
F	-	Geometrical shape factor
k	-	Thermal conductivity cal/cm-sec°C
x and y	-	Distance, meters
r	-	Radius, meters
R	-	Dimensionless ratio, r/h
h	-	Height, meters
o	-	Differential with respect to time, $\frac{d}{d\tau}$
q	-	Heat transfer rate, calories-unit time^{-1}
ϵ	-	Emissivity
α/ϵ	-	Solar absorptivity/emissivity infrared

Subscripts

t	-	Tank
s	-	Solar
m	-	Moon
p	-	Powder

APPENDIX B

HEAT BALANCE

1. Moon Surface

The lunar surface temperature is dependent upon the heat capacity of the moon, the sun rays angle φ, the emissivity of the moon with respect to shortwave radiation, and the radiation of the moon.

By ignoring topographical variations of the lunar surface and treating the moon as a sphere, a heat balance may be written for any given time during the daylight period:

$$S \quad \alpha_{sm} \, F_{sm} \quad dA_m - C\overset{o}{T}_m - \sigma T_m^{\,4} \, \epsilon_m \, dA_m = 0 \tag{1}$$

where from Appendix C,

$$F_{sm} = \cos \varphi = \sin\tau \, \cos\beta$$

Then assuming the moon to be perfectly insulated, we obtain: $C\overset{o}{T} = 0$. After substituting and rearranging terms, the temperature of the moon can be expressed as follows:

$$T_m = \left[\frac{S}{\sigma} \, \frac{\alpha_{sm}}{\epsilon m} \quad \sin\tau \quad \cos\beta \right]^{\frac{1}{4}} \qquad \begin{array}{l} 0 < \tau < \pi \\ T_m > 143^\circ K \end{array} \tag{2}$$

During the lunar night period, the surface temperature of the moon is considered to be constant, i.e.:

$$T_m = 143^\circ K \qquad \pi \leq \tau \leq 2\pi \tag{2a}$$

The temperature of an area of the lunar surface artificially covered with a special powder material can be determined for the lunar daylight period by substituting the α/ϵ value of the powder for the α/ϵ ratio of the lunar surface in equation (2), i. e.:

$$T_p = \left[\frac{S}{\sigma} \, \frac{\alpha_{sp}}{\epsilon_p} \sin\tau \, \cos\beta \right]^{\frac{1}{4}} \qquad 0 < \tau < \pi \tag{3}$$

If a powder material having approximately the same emissivity in the infrared wavelength as the lunar surface is used (T_iO_2), the temperature of the area during the lunar night period would be:

$$T_p = T_m = 143°K \qquad \pi \leq \tau \leq 2\pi \tag{3a}$$

2. Tank on Lunar Surface

The surface temperature of a tank located on the lunar surface during the lunar daylight period is dependent upon the heat capacity of the tank, the surface properties of the tank surface with respect to solar radiation, infrared and albedo from the moon,and radiation from the tank surface.

The average temperature of the tank surface during the daylight period is determined from the following heat balance:

$$S\,\alpha_{st}\,F_{ts}\,A_t + S\rho_m\,\alpha_{st}\,F_{tm}\cos\varphi\,A_t + \sigma T_m^{\,4}\,\epsilon_m\,\alpha_t\,F_{tm}\,A_t - C\overset{o}{T}_t - \sigma T_t^{\,4}\,\epsilon_t\,A_t = 0 \tag{4}$$

Considering the tank to be perfectly insulated ($C\overset{o}{T} = 0$), expressing the sun rays angle as before and, rearranging terms, we obtain the following expression for the average temperature of the tank surface during the lunar daylight period:

$$T_t = \left[\frac{S}{\sigma}\,\frac{\alpha_{st}}{\epsilon_t}\,F_{ts} + \frac{S}{\sigma}\,\frac{\alpha_{st}}{\epsilon_t}\,\rho_m\,F_{tm}\sin\tau\cos\beta + T_m^{\,4}\,\epsilon_m\,F_{tm}\right]^{\frac{1}{4}} \tag{5}$$

$$0 < \tau < \pi$$

where the temperature of the moon T_m is given by equation (2).

Equation (4) may also be used in conjunction with equation (2a) to determine the surface temperature of the tank during the lunar night period by neglecting the terms containing direct solar radiation S, i.e.:

$$T_t = \left[T_m^{\,4}\,\epsilon_m\,F_{tm}\right]^{\frac{1}{4}} \qquad T_m = 143°k \qquad \pi \leq \tau \leq 2\pi \tag{6}$$

The tank temperature at sunrise and sunset is determined from the following equation:

$$T_t = \left[S/\sigma \ \frac{\alpha_{ts}}{\epsilon_t} \ F_{ts} + T_m^{\ 4} \ \epsilon_m \ F_{tm} \right]^{\frac{1}{4}} \qquad \begin{array}{l} T_m = 143^\circ K \\ \tau = 0, \pi \end{array} \qquad (6a)$$

3. Tank on Coated Lunar Surface

A heat balance on a tank centrally located within a circular area exhibiting radiation properties like those of the tank surface is given by the following equation:

$$\begin{aligned} &S\alpha_{st} \ F_{ts} \ A_t + S\rho_p \ \alpha_{st} \ F_{tp} \ \cos\varphi \ A_t + S\rho_m \ \alpha_{st} \ F_{tm} \ \cos\varphi \ AT \\ &+ \sigma T_m^{\ 4} \ \epsilon_m \ \alpha_t \ F_{tm} \ A_t + \sigma T_p^{\ 4} \ \epsilon_p \ \alpha_t \ F_{tp} \ A_t \qquad (7) \\ &- C\overset{o}{T}_t - \sigma T_t^{\ 4} \ \epsilon_t \ A_t = 0 \end{aligned}$$

Again, considering the tank to be perfectly insulated ($C\overset{o}{T} = 0$), expressing the sun ray's angle as before and rearranging terms, we obtain an expression for the tank surface temperature during the daylight period:

$$\begin{aligned} T_t = \Bigg[&\frac{S}{\sigma} \ \frac{\alpha_{st}}{\epsilon_t} \ F_{ts} + \frac{S}{\sigma} \ \frac{\alpha_{st}}{\epsilon_t} \ \rho_p \ F_{tp} \ \sin\tau \ \cos\beta \qquad (8) \\ &+ \frac{S}{\sigma} \ \frac{\alpha_{st}}{\epsilon_t} \ \rho_m \ F_{tm} \ \sin\tau \ \cos\beta \ + T_m^{\ 4} \ \epsilon_m \ F_{tm} + T_p^{\ 4} \epsilon_p F_{tp} \Bigg]^{\frac{1}{4}} \end{aligned}$$

$$0 < \tau < \pi$$

where T_m and T_p are given by equations (2) and (3), respectively.

Assuming the radiation properties of the tank surface and the coated area to be the same, and noting from Appendix C that $F_{Tm} = 0.5 - F_{Tp}$, equation (8) may be rewritten for the daylight period as:

$$\begin{aligned} T_t = \Bigg[\frac{S}{\sigma} \Bigg\{ &\frac{\alpha_{st}}{\epsilon_t} \ F_{ts} + \sin\tau \ \cos\beta \left[\left(F_{tp} \ (\rho_t - \rho_m) + 0.5 \ \rho_m \right) \left(\frac{\alpha_{st}}{\epsilon_t} - 1 \right) \right. \\ &\left. + 0.5 \ \right] \Bigg\} \Bigg]^{\frac{1}{4}} \qquad 0 < \tau < \pi \qquad (9) \end{aligned}$$

The surface temperature of the tank during the night period is determined from equation (8) by ignoring the terms containing direct solar radiation, i.e.:

$$T_t = \left[T_m^{\ 4} \ \epsilon_m \ F_{tm} + T_p^{\ 4} \ \epsilon_p \ F_{tp} \right]^{\frac{1}{4}} \qquad \pi \leq \tau \leq 2\pi \tag{10}$$

Assuming the emissivity and temperature of the powdered surface and the moon surface to be equal, equation (10) may be rewritten as:

$$T_t = \left[T_m^{\ 4} \ \epsilon_m \left(F_{tm} + F_{tp} \right) \right]^{\frac{1}{4}} \qquad \begin{array}{l} \pi \leq \tau \leq 2\pi \\ T_m = T_p = 143^\circ K \end{array} \tag{10a}$$

The tank temperature at sunrise and sunset is determined from the following equation:

$$T_t = \left\{ S/\sigma \left[\frac{\alpha_{ts}}{\epsilon_t} \ F_{ts} + T_m^{\ 4} \ \epsilon_m \ F_{tm} + T_p^{\ 4} \ \epsilon_p \ F_{tp} \right] \right\}^{\frac{1}{4}} \tag{10b}$$

$$\epsilon_p \cong \epsilon_m \qquad T_m = T_p = 143^\circ K \qquad \tau = 0, \pi$$

APPENDIX C

SHAPE FACTORS

1. Moon Surface

The shape factor for an element area tangent to the lunar surface and receiving solar radiation is equal to the projected area of the element divided by the total area of the element. Since the ecliptic plane and the lunar equatorial plane are inclined only 1° 32', they may be considered to be coplanar, which permits the area ratio to be written as:

$$F_{ms} = \cos\varphi^{*} \quad (1)$$

Applying the law of direction cosines, and with the aid of FIGURE 13, it is seen that

$$F_{ms} = \sin \tau \cos \beta \quad (2)$$

2. Spherical Tank

The shape factor for a spherical tank located on the lunar surface was determined by assuming that the area of the lunar surface within the horizon of the tank was an infinite plane. Thus, the value of the shape factor would be equal to:

$$F_{tm} = 0.5 \quad (3)$$

During the daylight period, the shape factor of the spherical tank, with respect to incoming solar irradiation is equal to the projected area of the tank divided by the total surface area, i. e.:

$$F_{ts} = \frac{\pi r^2}{4\pi r^2} = 0.25 \quad (4)$$

---

* Reported as COS $^{2/3}\varphi$ in ABMA report DV-TN-21-59, "Temperatures on the Moon," by Klaus Schocken. The value is an empirical relation expressing measured values of the lunar surface temperature at the lunar equatorial plane. The use of the cos φ results in a temperature difference of approximately 10°K as reported in the aforementioned report.

3. Spherical Tank in the Center of Circular Surface Area with Finite Radius

The shape factor of a spherical tank centrally located within a circular powder covered area on the lunar surface was established from FIGURE 14. The shape factor is equal to the projected area divided by the total surface area, which, from the figure is:

$$F_{tp} = \frac{2\pi r^2 - 2\pi r^2 \sin\theta}{4\pi r^2} = \frac{1}{2}(1 - \sin\theta) \tag{5}$$

where

$$\theta = \cot^{-1} R/r$$

The shape factor for the uncovered region of the moon within the tank's horizon was deduced to be:

$$F_{tm} = 0.5 - F_{tp} \tag{6}$$

4. Shrouded Tank

Before the shape factors for a shrouded spherical tank on the lunar surface are derived, it is necessary to determine the shape factor of an element area radiating to a plane surface.

The shape factor of an element area radiating to a finite area is given as follows: (Ref. 1)

$$F_{1-2} = \int \frac{\cos\beta_1 \cos\beta_2 \, dA_2}{\pi S^2} \tag{7}$$

From this equation, the shape factor of a centrally located elemental area radiating from one side to a circular area can be determined. The following relationships were established from FIGURES 15 and 16.

$$\cos\beta_1 = \frac{1}{S}(h \sin\theta + x \cos\theta) \qquad dA_2 = dx\, dy$$

$$\cos\beta_2 = h/s \qquad S^2 = x^2 + y^2 + h^2$$

Substitution of these values into equation (7) yields:

$$F_{1-2} = 2\int_{-h\cot\theta}^{r}\int_{0}^{(r^2-x^2)^{\frac{1}{2}}} \frac{h\,(h\cos\theta + x\sin\theta}{\pi\,(x^2+y^2+h^2)^2}\,dx\,dy \tag{8}$$

$$-r \leq -h\cot\theta \leq r$$

Integration of equation (8) results in:

$$F_{1-2} = \frac{h\cos\theta}{\pi}\left\{\frac{\pi}{2h}\left(\frac{r^2}{r^2+h^2}\right) - \frac{r^2\sin^{-1}\left(-\frac{h\cot\theta}{r}\right)}{h\,(r^2+h^2)}\right. \tag{8a}$$

$$\left. + \frac{\cot\theta\ \cos^{-1}\left[h\left(\frac{\cot^2\theta+1}{r^2+h^2}\right)^{\frac{1}{2}}\right]}{h\,(\cot^2\theta+1)^{\frac{1}{2}}}\right\} - \frac{h\sin\theta}{\pi}\left\{\frac{(r^2-h^2\cot^2\theta)^{\frac{1}{2}}}{r^2+h^2}\right.$$

$$\left. - \frac{\cos^{-1}\left[h\left(\frac{1+\cot^2\theta}{r^2+h^2}\right)^{\frac{1}{2}}\right]}{h\,(1+\cot^2\theta)^{\frac{1}{2}}}\right\} \qquad -r \leq -h\cot\theta \leq r$$

By introducing the relations: $r = Rh$ where $h = 1$, it follows that equation (8a) can be written as:

$$F_{1-2} = \frac{\cos\theta}{\pi}\left\{\cot\theta\ \cos^{-1}\left(\frac{\cot^2\theta+1}{R^2+1}\right)^{\frac{1}{2}} - \frac{R^2}{R^2+1}\,\mathrm{SIN}^{-1}\left(-\frac{\cot\theta}{R}\right)\right. \tag{8b}$$

$$\left. + \frac{\cot\theta\ \cos^{-1}\left(\frac{\cot^2\theta+1}{R^2+1}\right)^{\frac{1}{2}}}{(\cot^2\theta+1)^{\frac{1}{2}}}\right\} - \frac{\sin\theta}{\pi}\left\{\frac{(R^2-\cot^2\theta)^{\frac{1}{2}}}{R^2+1}\right.$$

$$\left. - \frac{\cos^{-1}\left(\frac{\cot^2\theta+1}{R^2+1}\right)^{\frac{1}{2}}}{(\cot^2\theta+1)^{\frac{1}{2}}}\right\} \qquad -R \leq -\cot\theta \leq R$$

FIGURE 17 presents a graphical interpretation of this equation for various values of the parameter R. Of interest is the curve for R = ∞ which yields:

$$F_{1-2} = \frac{1}{2}\,(1 + \cos\theta) \tag{9}$$

The shaped factor of a shrouded spherical tank with respect to the moon may be calculated with the aid of the foregoing derivation. Assuming that the area seen by the tank is an infinite plane, equation (9) may be used to determine the shape factor. With the aid of FIGURE 18, and noting that the surface area of the lower half of the tank is the same as the surface area of the shroud, the following relationship is established:

$$F_{tm} = \frac{\int F\,dA_{\text{Spherical Section}} + \int F\,dA_{\text{Shrouded Section}}}{A_{\text{Spherical Section}} + A_{\text{Shrouded Section}}} \tag{10}$$

where the shape factor for the spherical section is given by the expression F = 1/2 (1- SIN γ) which was determined from equation (9) by substituting 0 = 90°+ γ.

As shown, the surface area of the shroud is the same as the lower portion of the sphere. By assuming the shroud is a good conductor with the same surface properties as the uncovered portion of the tank and, in addition, that black body radiation occurs between the shroud and the lower portion of the sphere, the shape factor of the lower half of the tank is determined to be equal to 0.5, i.e., $F_{\text{shroud to moon}} = 0.5$. Introducing these values into equation (10) yields:

$$F_{tm} = \frac{\frac{2\pi r^2}{2} \int_0^{\pi/2} (1 - \sin\gamma)\cos\gamma\, d\gamma + 0.5 \times 2\pi r^2}{4\pi r^2} \tag{10a}$$

Integration of equation (10a) determines the shape for the tank with respect to the moon as:

$$F_{tm} = 0.375 \tag{11}$$

The shape factor of this tank with respect to solar radiation is determined from FIGURE 18 by dividing the projected area by the total surface area of the tank. Again,it is necessary to assume that black body radiation occurs between the shroud and the bottom of the tank. As shown, this factor can be expressed as a function of the sun rays angle, i.e.:

$$F_{ts} = \frac{\frac{\pi r^2}{2} + 2 \sin\varphi \; r^2 + \frac{\pi r^2}{2} \cos \varphi}{4\pi r^2} \qquad (12)$$

Rearranging terms and expressing the sun rays angle as a function of the time angle τ and the latitude angel β yields:

$$F_{ts} = \frac{1}{8\pi} \left[\pi + 4 \left(1 - \sin^2\tau \cos^2\beta\right)^{\frac{1}{2}} + \pi \sin\tau \cos \beta \right]$$

APPENDIX D

HEAT FLUX CALCULATIONS

1. Above-Ground Storage

The value of the heat flux into several LH_2 storage tank configurations located on the lunar surface at the equator was determined for a complete lunar cycle. The tanks were considered to be insulated with 0.0508 meters (2 inches) of SI-62 type insulation and painted on its exterior with TiO_2 paint. The tank was considered to be vented at one atmosphere of pressure, thus maintaining the hydrogen at an equilibrium temperature of 20°K. In addition, it was assumed that no film resistance occurs between the interior surface of the tank and the LH_2 liquid and vapor.

For these conditions, the heat flux at any time can be represented by the Fourier conduction equation: $q/A = dt/dx$. However, since the surface temperature of a tank varies during the lunar cycle, it was necessary to compute the heat flux for small time increments, i.e.:

$$(q/A)_{\text{Cycle}} = \frac{1}{\Delta x} \sum_{n=1}^{m} k_n \, \Delta T_n$$

where m equals the total number of selected increments in a lunar cycle.

This equation also permits any variation of thermal conductivity with surface temperature to be taken into account (FIGURE 19).

With the aid of FIGURES 3, 5, and 11, and a time increment of 19.7 hours ($\Delta \tau = 10°$), the heat flux of a spherical tank, a shrouded tank, and a spherical tank centrally located in a circular powder-covered area of radius R = 4 were determined to be 70.5, 63.2, and 53.8 kilocalories-square meter^{-1} cycle^{-1}, respectively.

2. Below-Ground Storage

The steady state heat flux into a spherical tank containing LH_2 and located beneath the lunar surface was determined for one lunar cycle. With the tank insulated and vented as described in subsection (1), and the subsurface temperature considered constant at 233°K, the heat flux for a lunar cycle is 70.7 kilocalories-square meter^{-1}cycle^{-1}.

APPENDIX E

STORAGE TIME

The storage period in which a liquid fuel may be stored on the moon is determined by the net total heat flux received or given up by the fuel during its storage. To interpret the heat fluxes obtained in Appendix C, the following example is offered:

Assume that 13,600 kilograms of LH_2 are stored at approximately one atmosphere of pressure on a region of the moon where the heat flux penetrating the insulation (0.0508 meters thick) is 70.0 kilocalories-square meter^{-1}cycle^{-1}. This heat flux is chosen, as it determines the storage time for above-ground and below-ground conditions. It will further be assumed that an equal amount of heat flux is conducted through structural supports. Under these conditions, the LH_2 may be stored approximately six completed lunar cycles (177.5 days) with only 10 percent of the initial amount having been vented during the storage period.

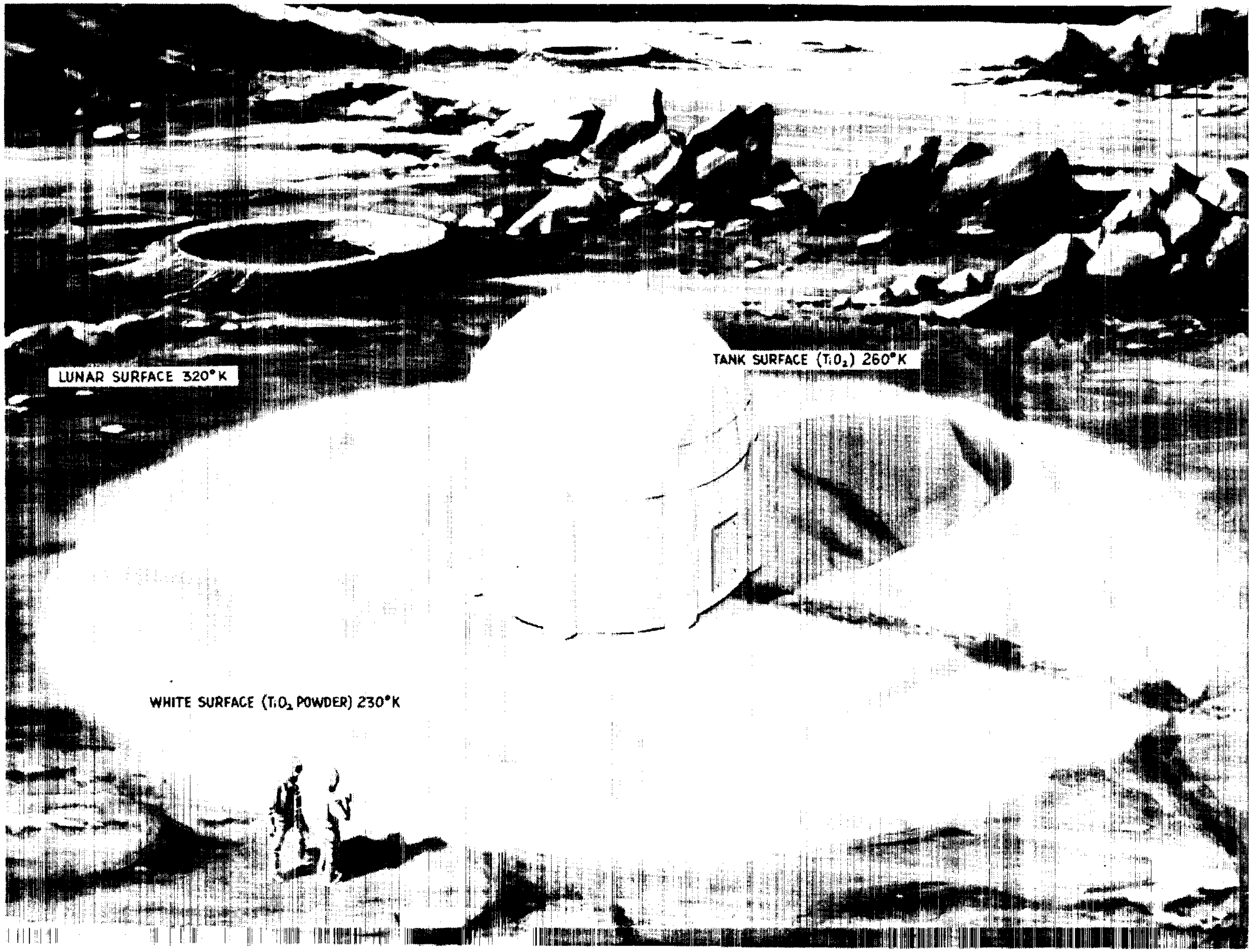

FIGURE 1. LUNAR PROPELLANT DEPOT

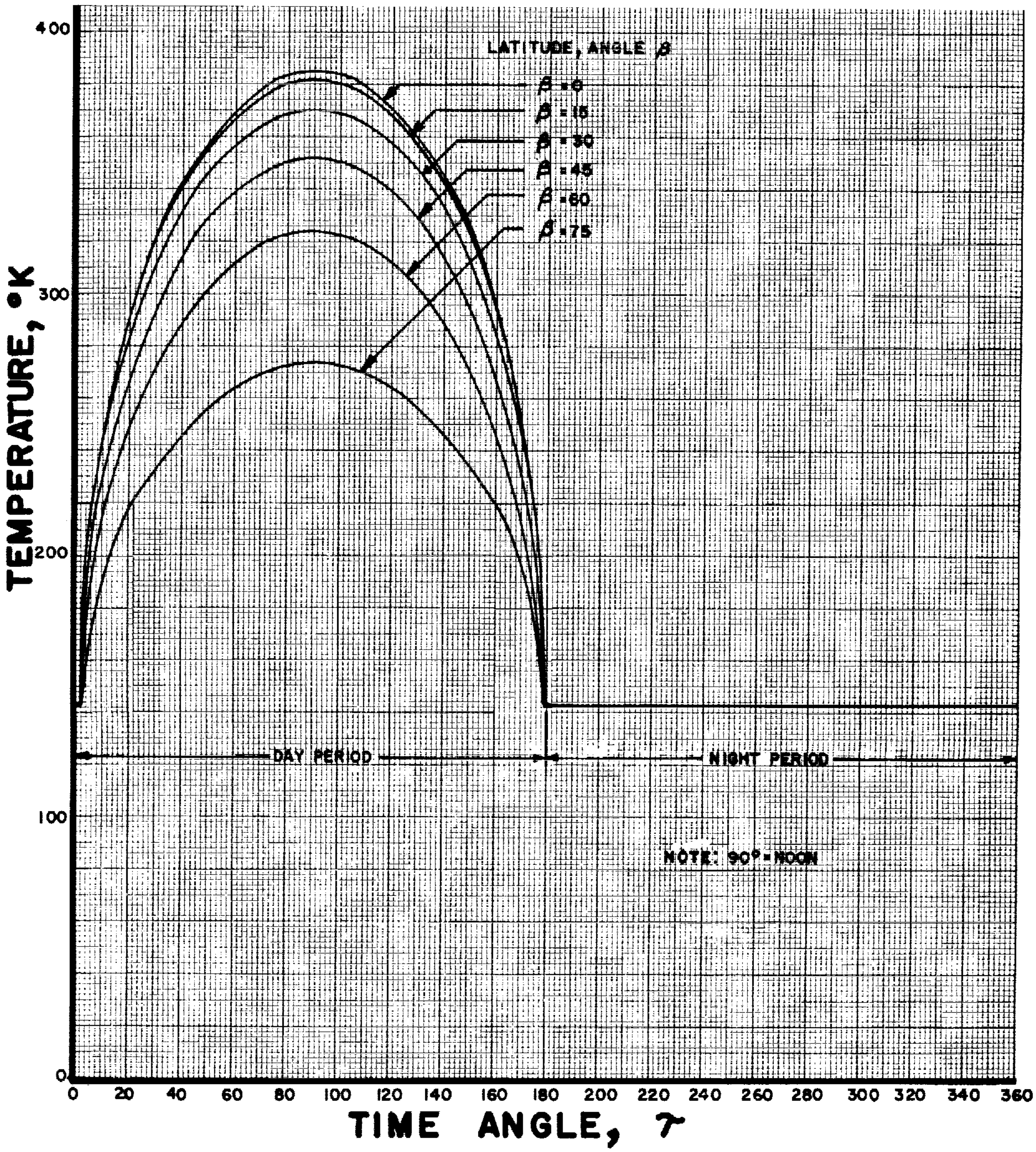

FIGURE 2. LUNAR SURFACE TEMPERATURE AT VARIOUS LATITUDES VS. TIME ANGLE

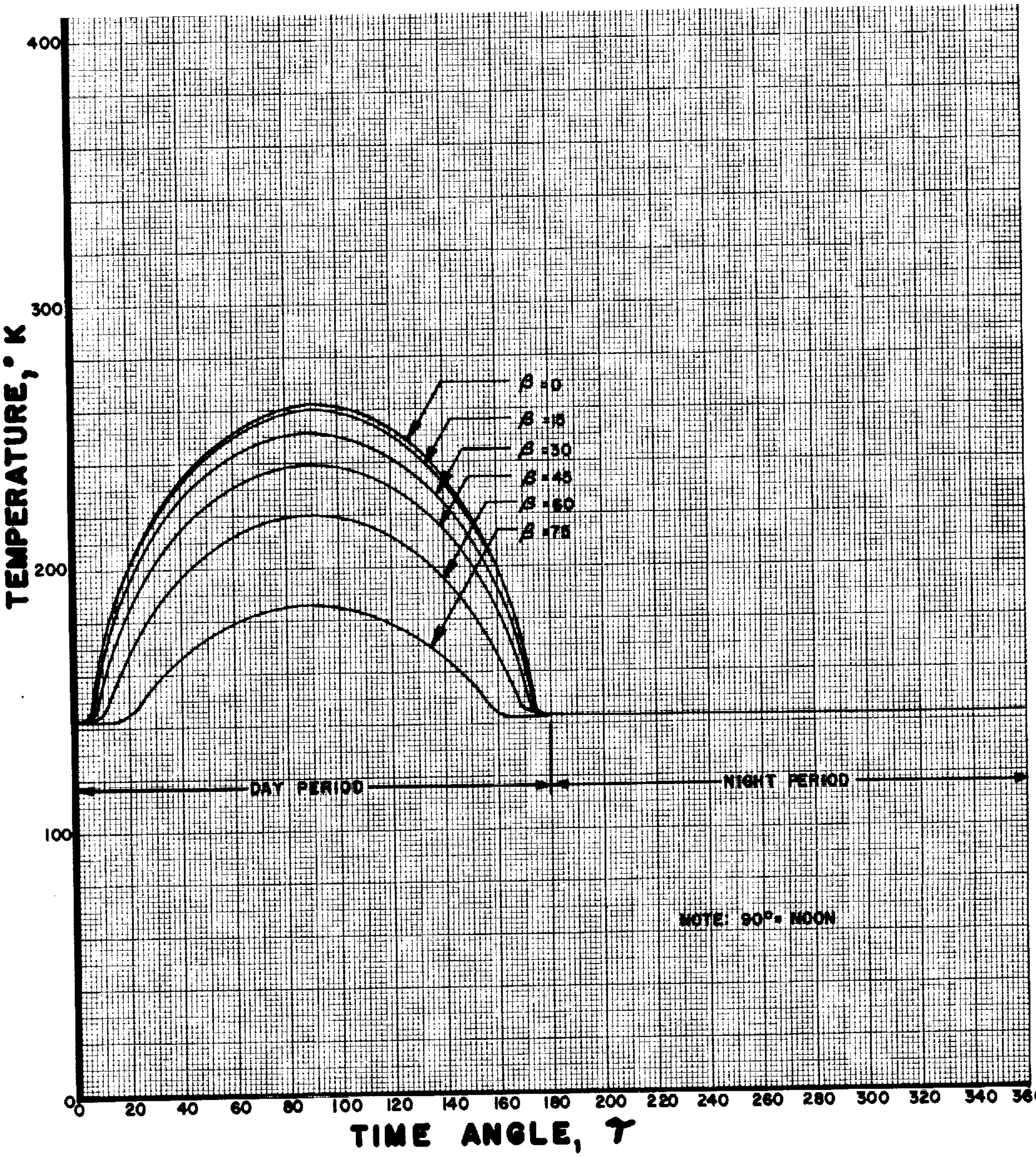

FIGURE 3. ALTERED LUNAR SURFACE TEMPERATURE (TiO_2) AT VARIOUS LATITUDES VS. TIME ANGLE

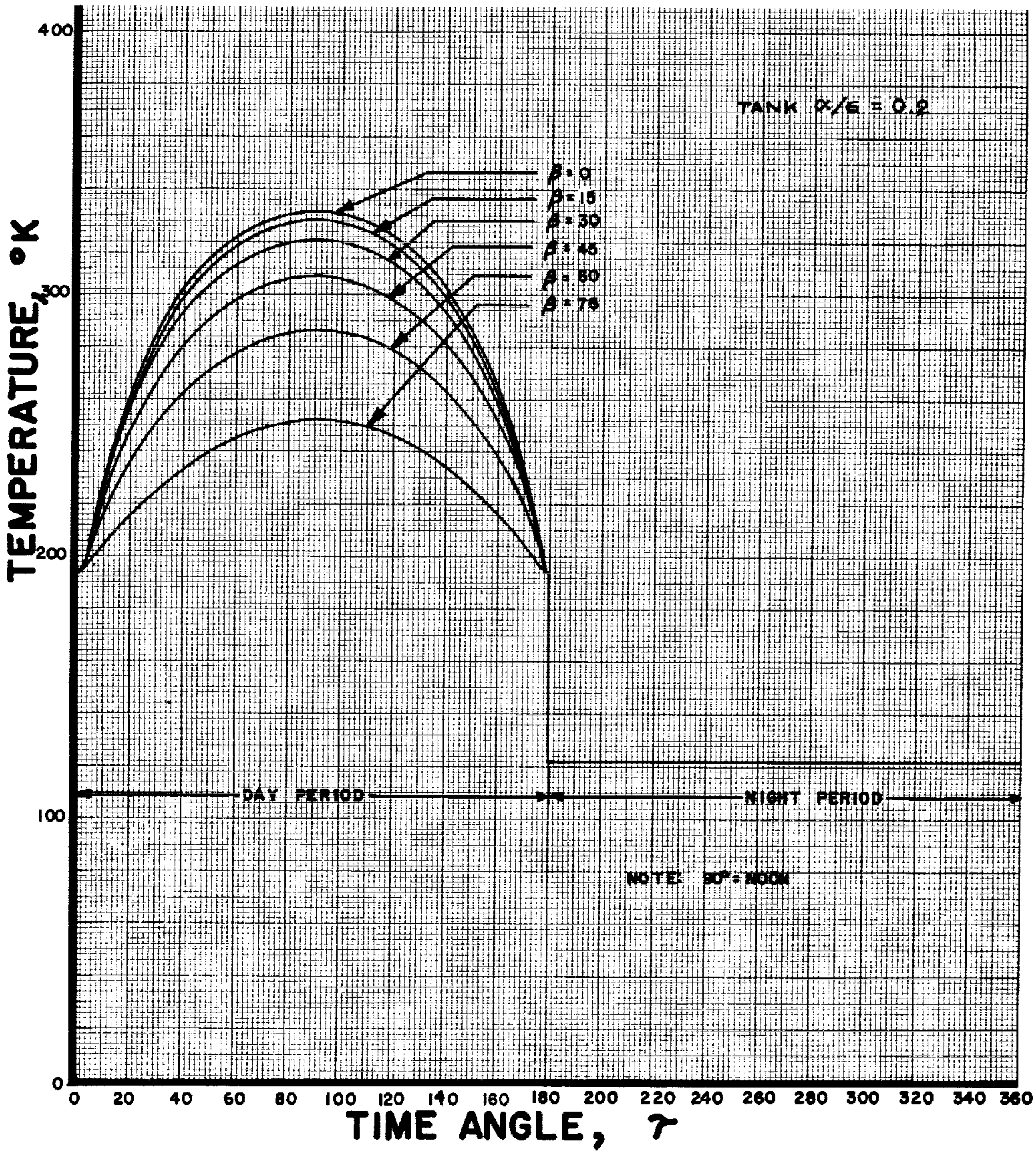

FIGURE 4. SURFACE TEMPERATURE OF A SPHERICAL TANK AT VARIOUS LATITUDES VS. TIME ANGLE

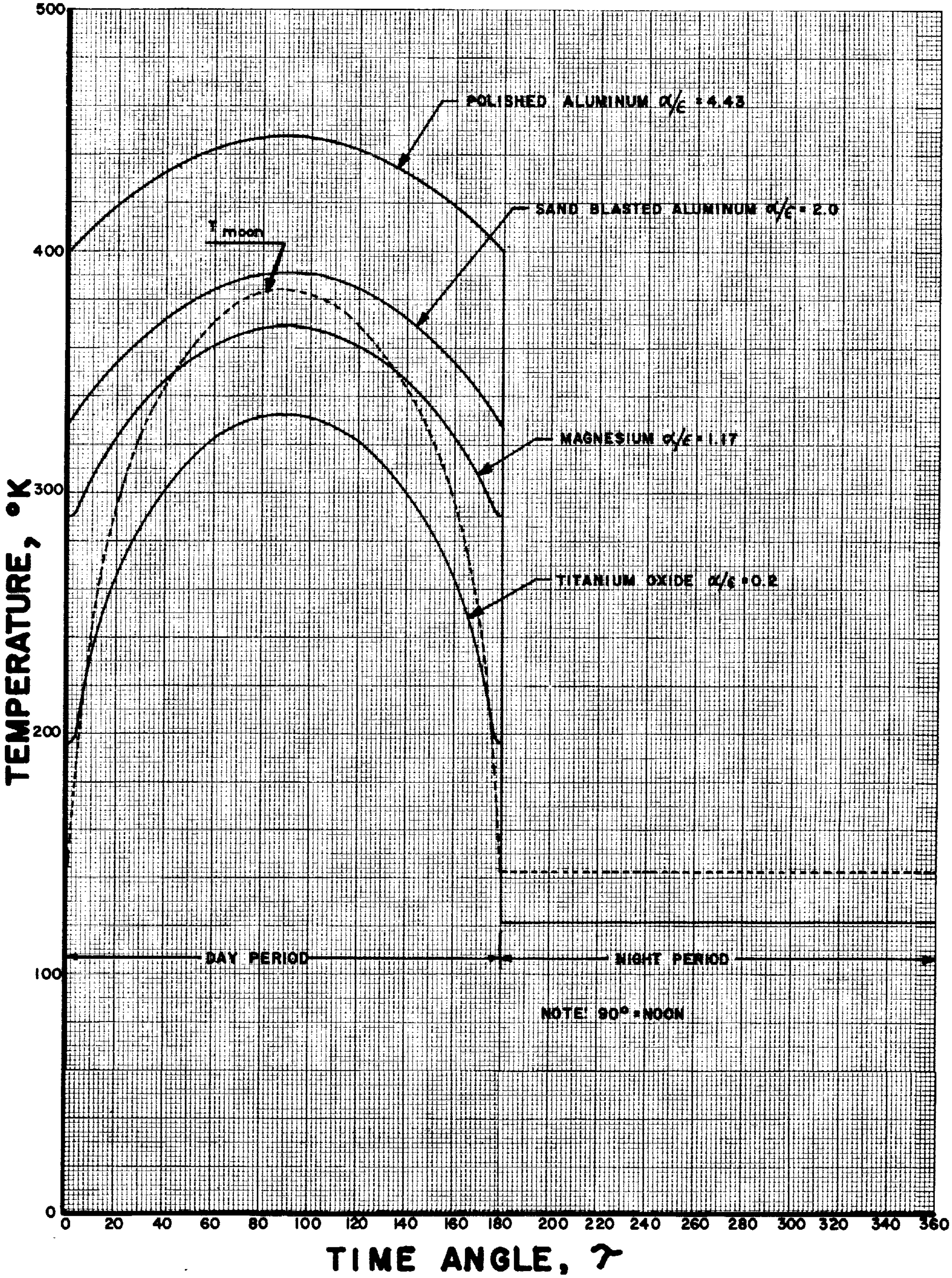

FIGURE 5. SURFACE TEMPERATURE OF SPHERICAL TANK WITH VARIOUS α/ϵ VALUES (0° LATITUDE) VS. TIME ANGLE

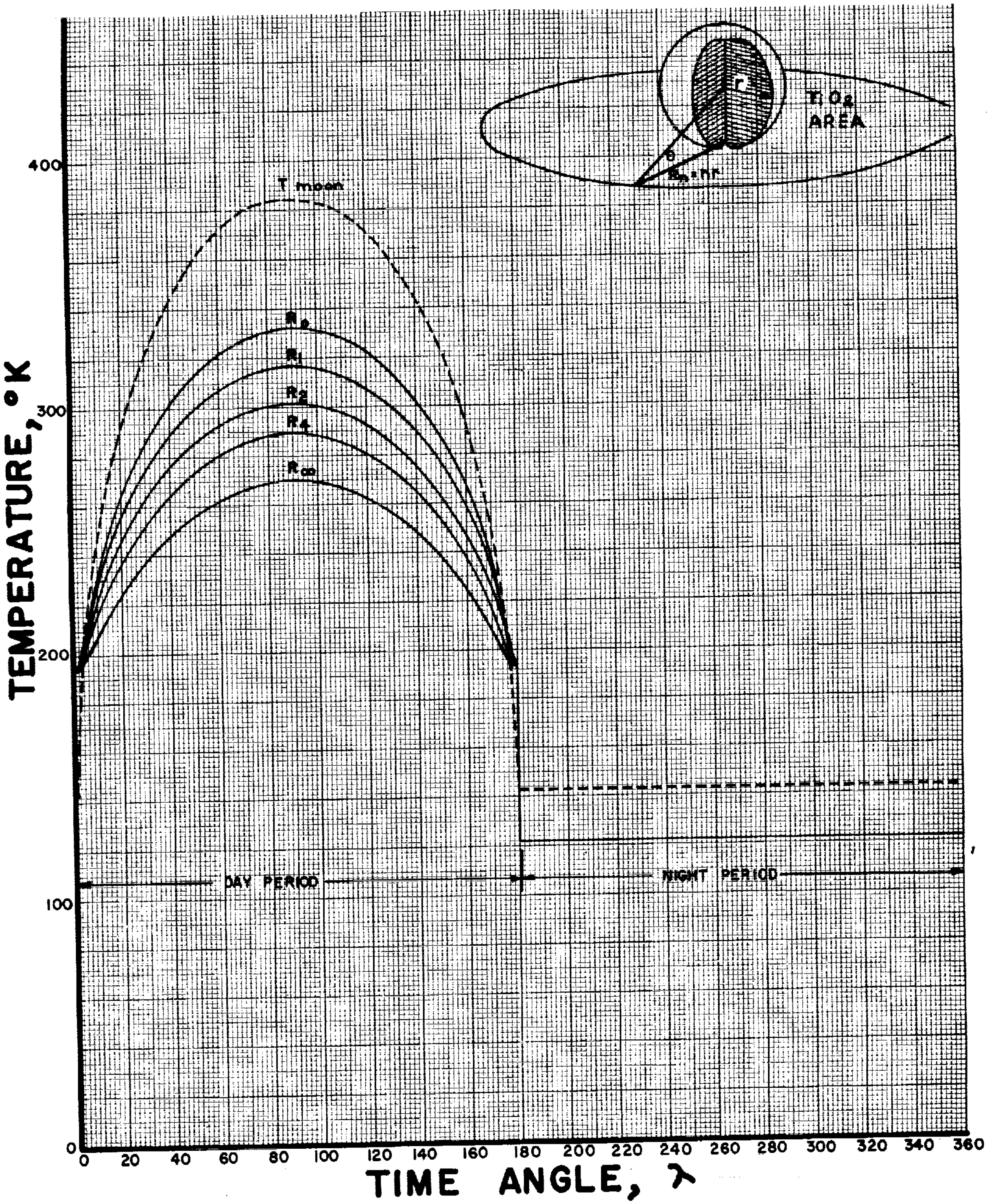

FIGURE 6. SURFACE TEMPERATURE OF SPHERICAL TANK CENTRALLY LOCATED ON VARIOUS SIZE CIRCULAR AREAS OF LUNAR SURFACE ALTERED TO $\alpha/\epsilon = 0.2$ VS. TIME ANGLE (LATITUDE = 0°)

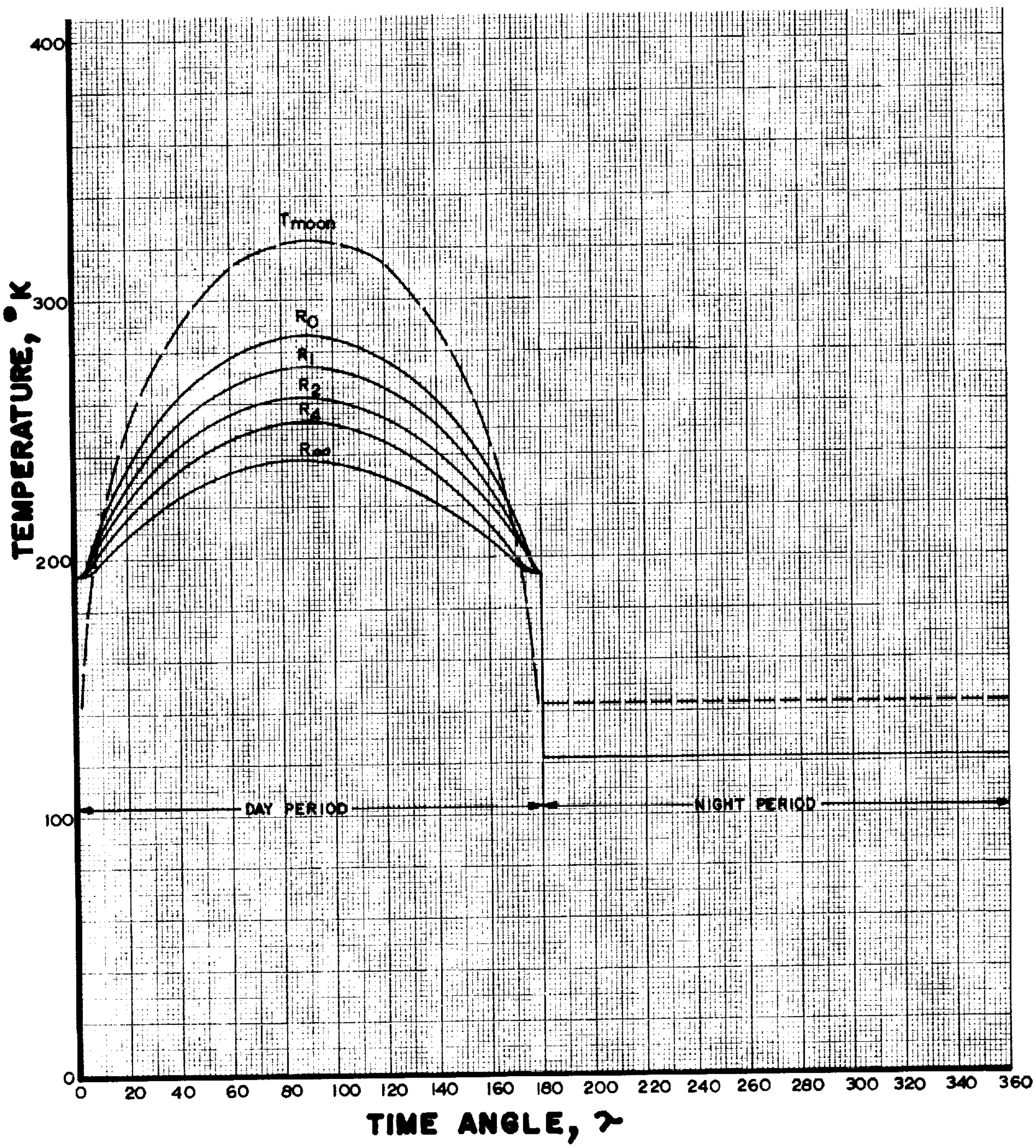

FIGURE 10. SURFACE TEMPERATURE OF SPHERICAL TANK CENTRALLY LOCATED ON VARIOUS SIZE CIRCULAR AREAS OF LUNAR SURFACE ALTERED TO α/ϵ = 0.2 VS. TIME ANGLE (LATITUDE = 60°)

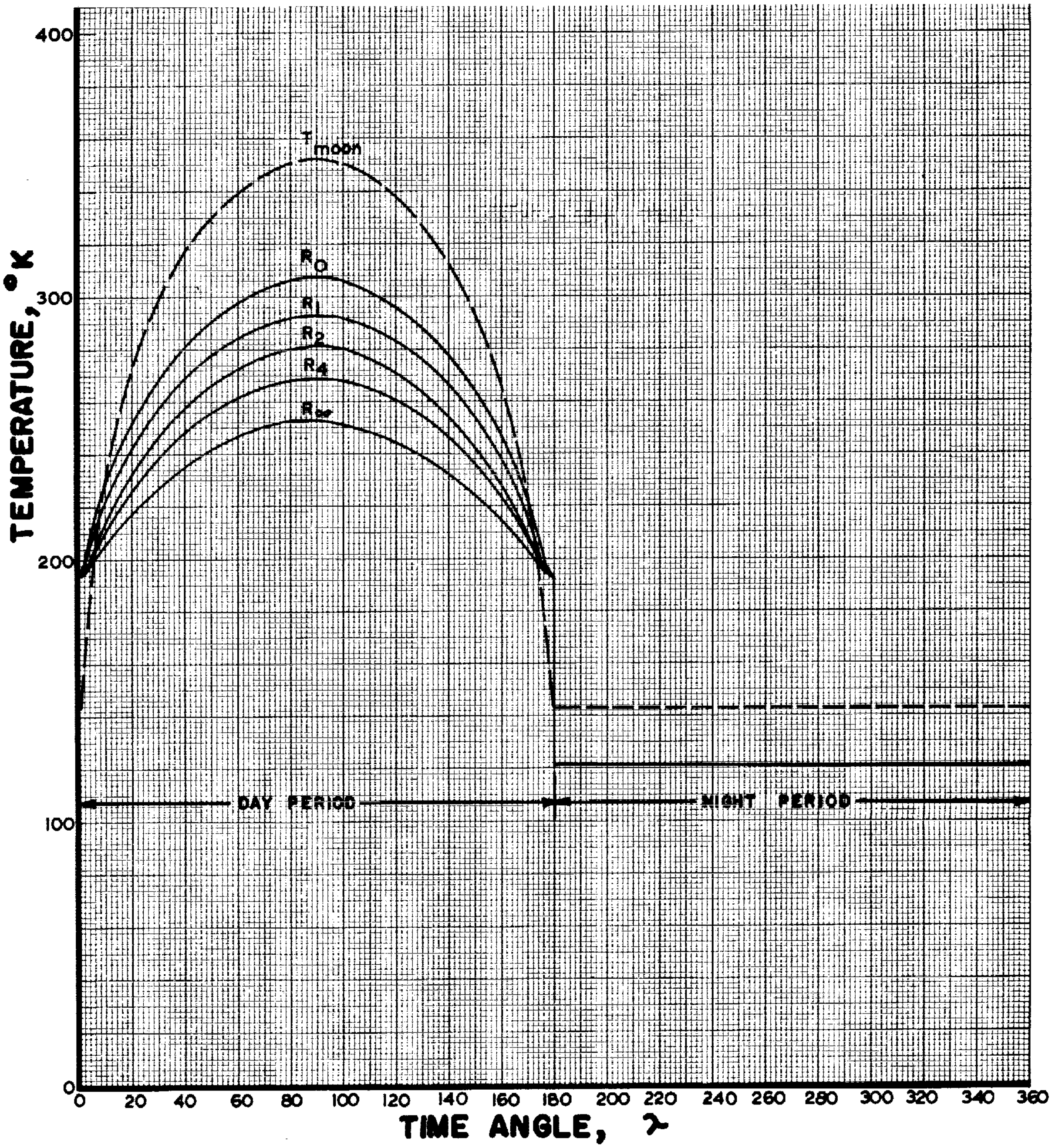

FIGURE 9. SURFACE TEMPERATURE OF SPHERICAL TANK CENTRALLY LOCATED ON VARIOUS SIZE CIRCULAR AREAS OF LUNAR SURFACE ALTERED TO $\alpha/\epsilon = 0.2$ VS. TIME ANGLE (LATITUDE = 45°)

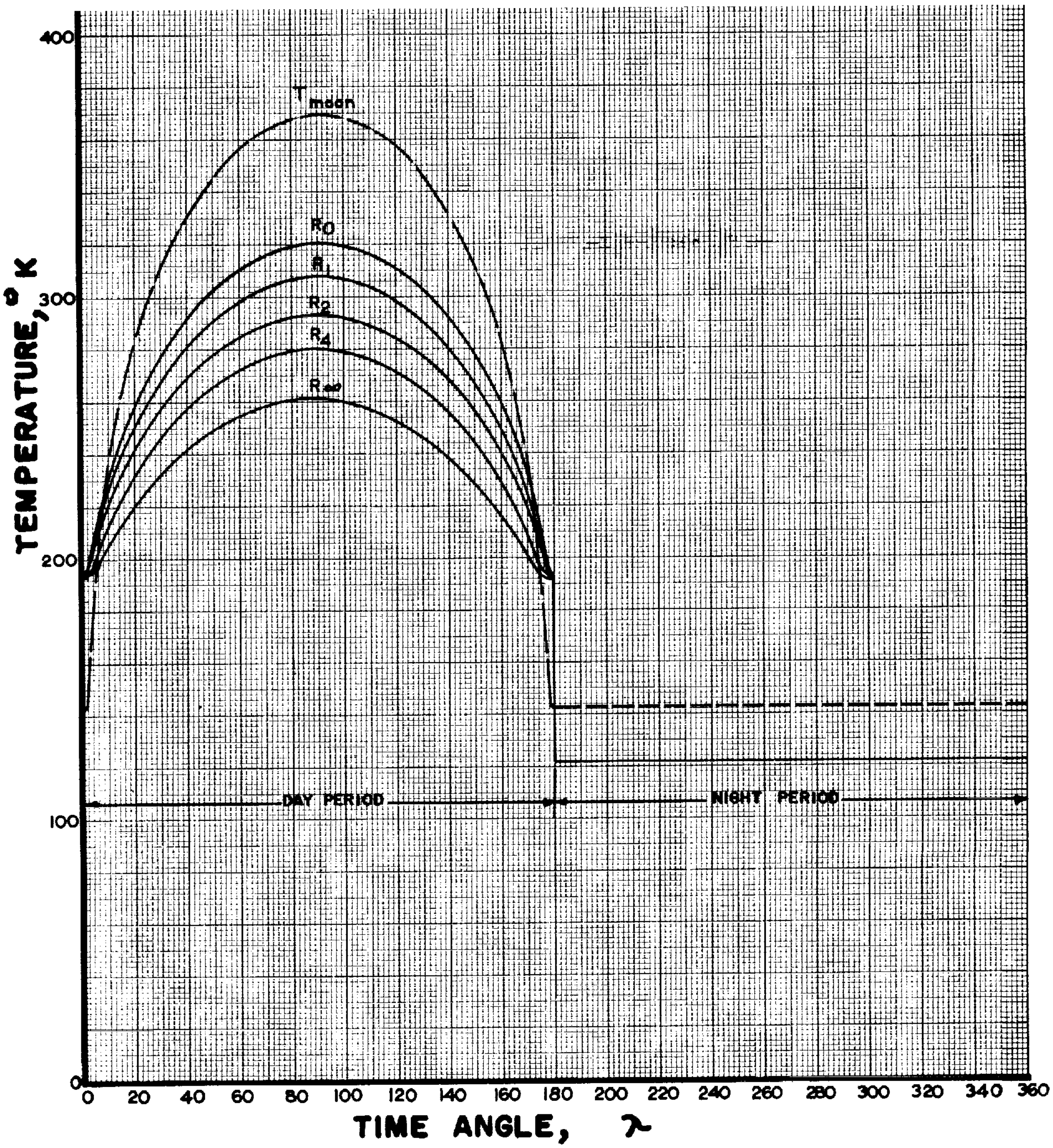

FIGURE 8. SURFACE TEMPERATURE OF SPHERICAL TANK CENTRALLY LOCATED ON VARIOUS SIZE CIRCULAR AREAS OF LUNAR SURFACE ALTERED TO $\alpha/\epsilon = 0.2$ VS. TIME ANGLE (LATITUDE = 30°)

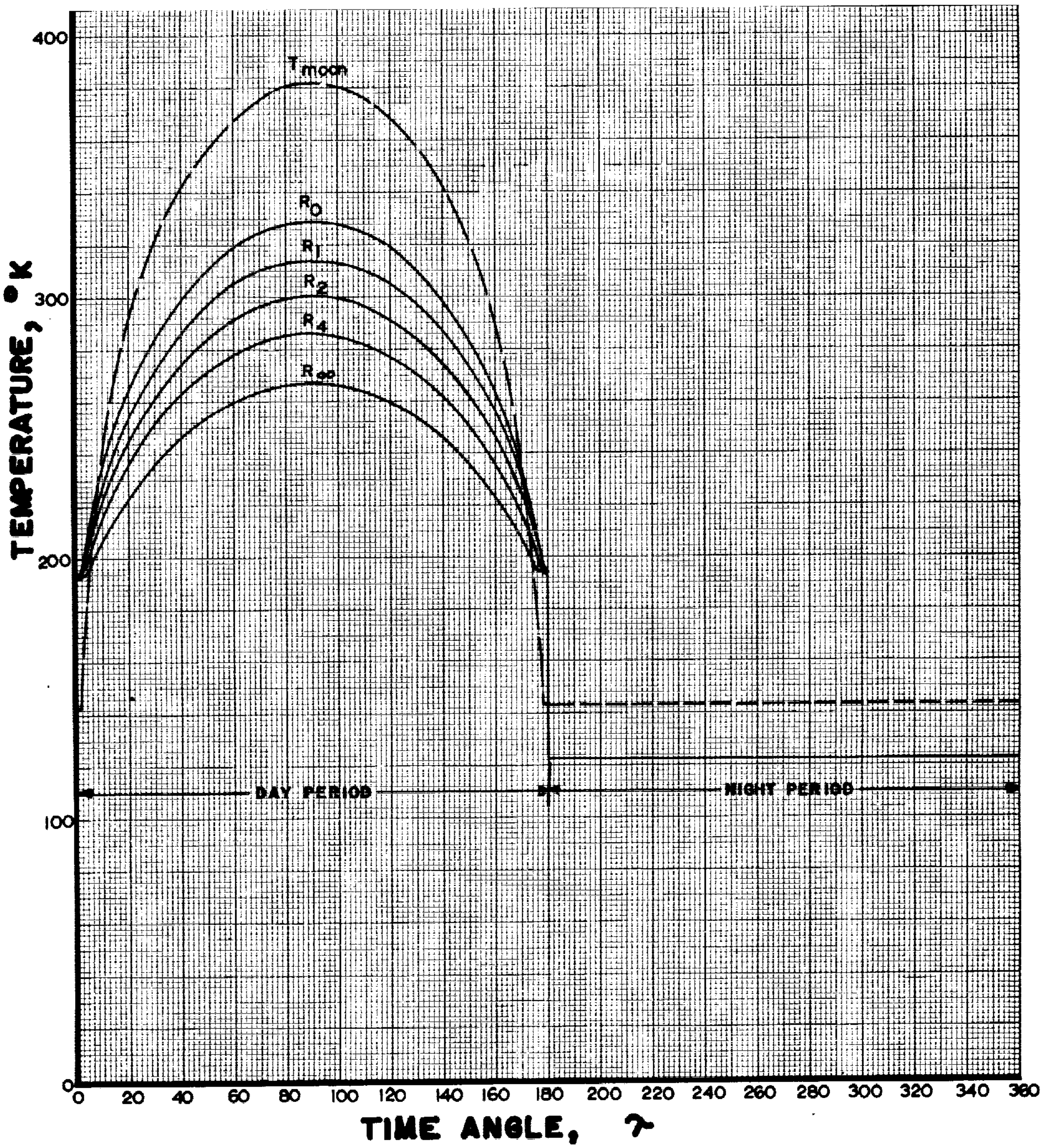

FIGURE 7. SURFACE TEMPERATURE OF SPHERICAL TANK CENTRALLY LOCATED ON VARIOUS SIZE CIRCULAR AREAS OF LUNAR SURFACE ALTERED TO α/ϵ = 0.2 VS. TIME ANGLE (LATITUDE = 15°)

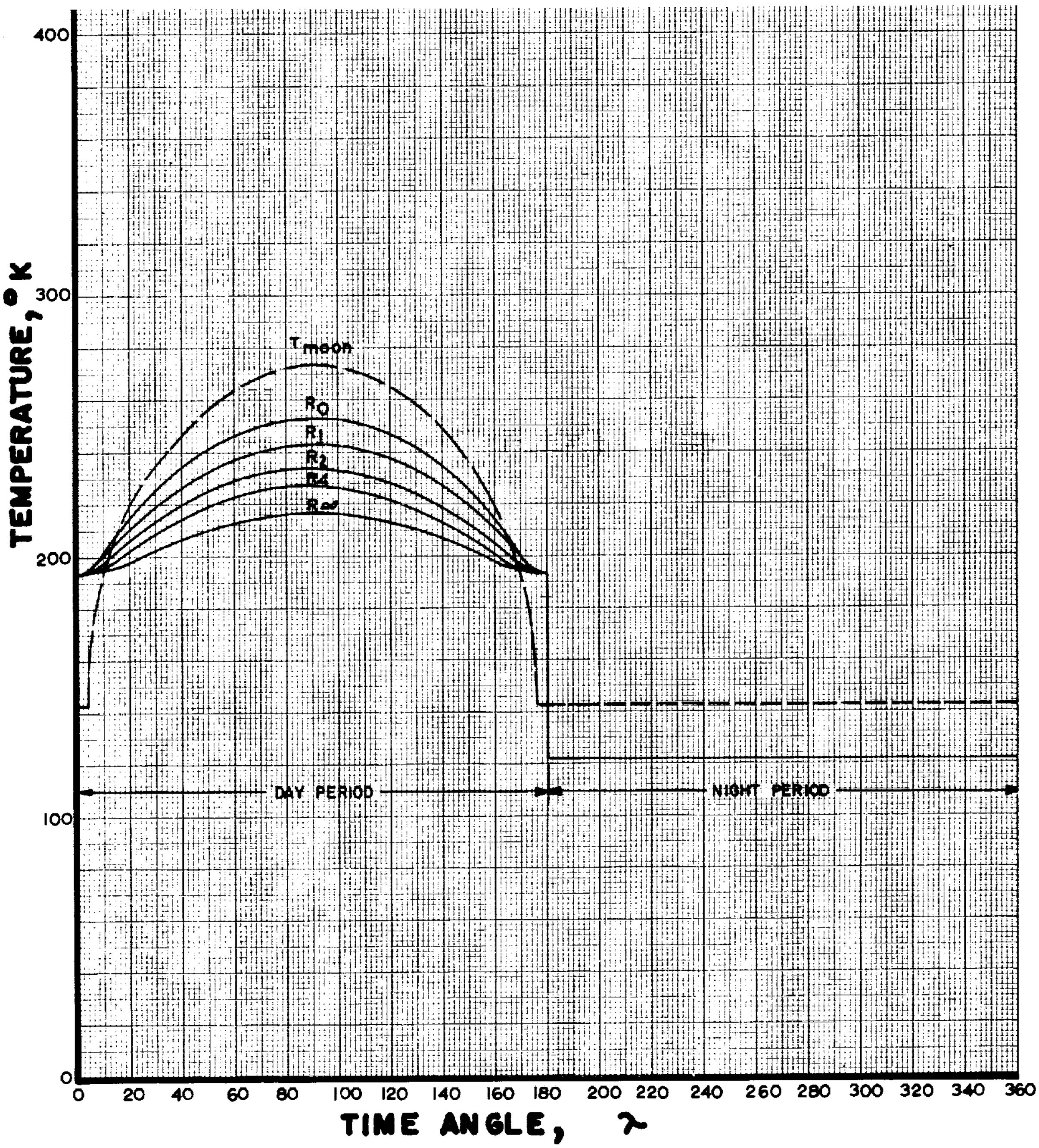

FIGURE 11. SURFACE TEMPERATURE OF SPHERICAL TANK CENTRALLY LOCATED ON VARIOUS SIZE CIRCULAR AREAS OF LUNAR SURFACE ALTERED TO α/ϵ = 0.2 VS. TIME ANGLE (LATITUDE = 75°)

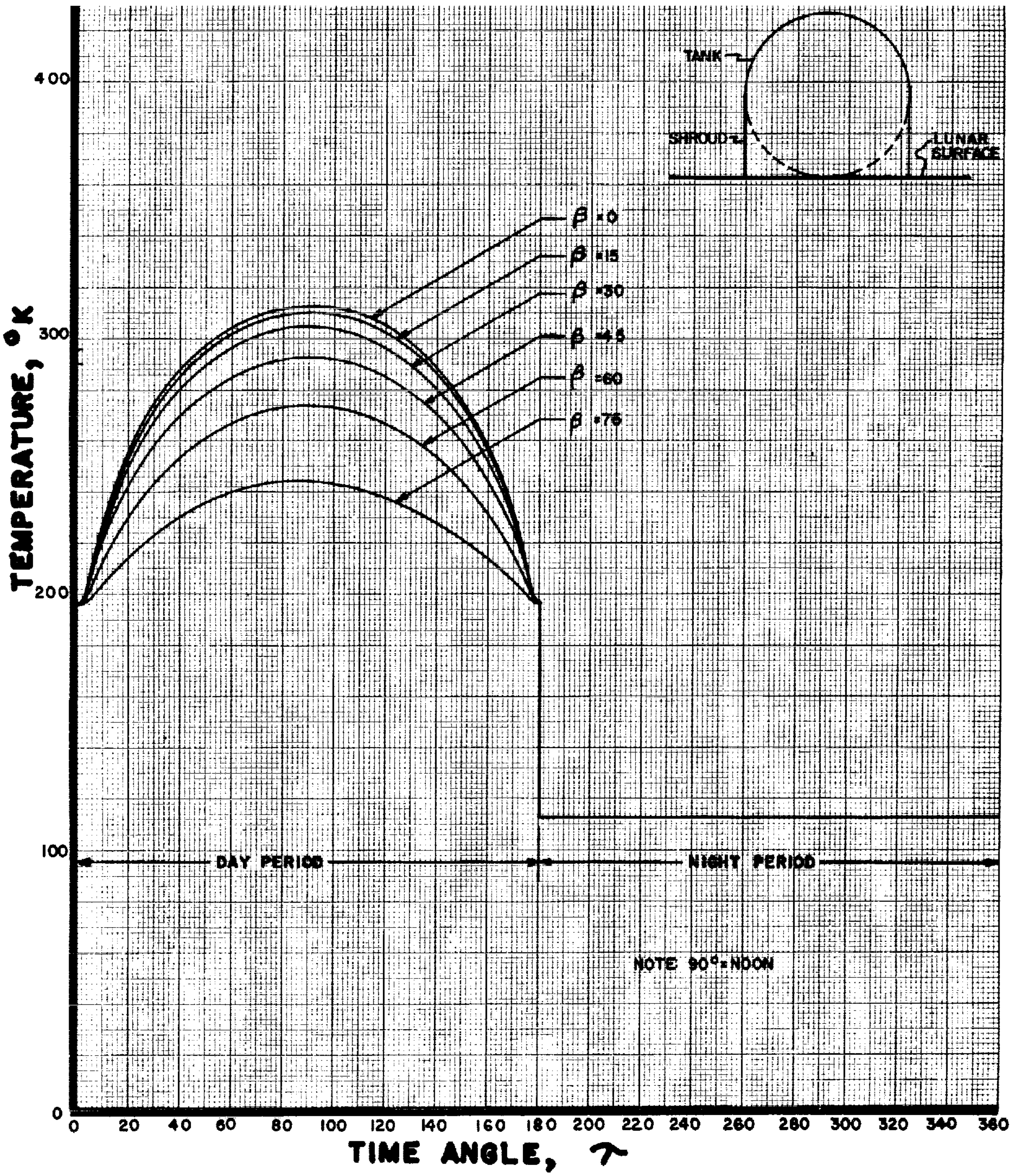

FIGURE 12. SURFACE TEMPERATURE OF A SHROUDED SPHERICAL TANK AT VARIOUS LATITUDES VS. TIME ANGLE

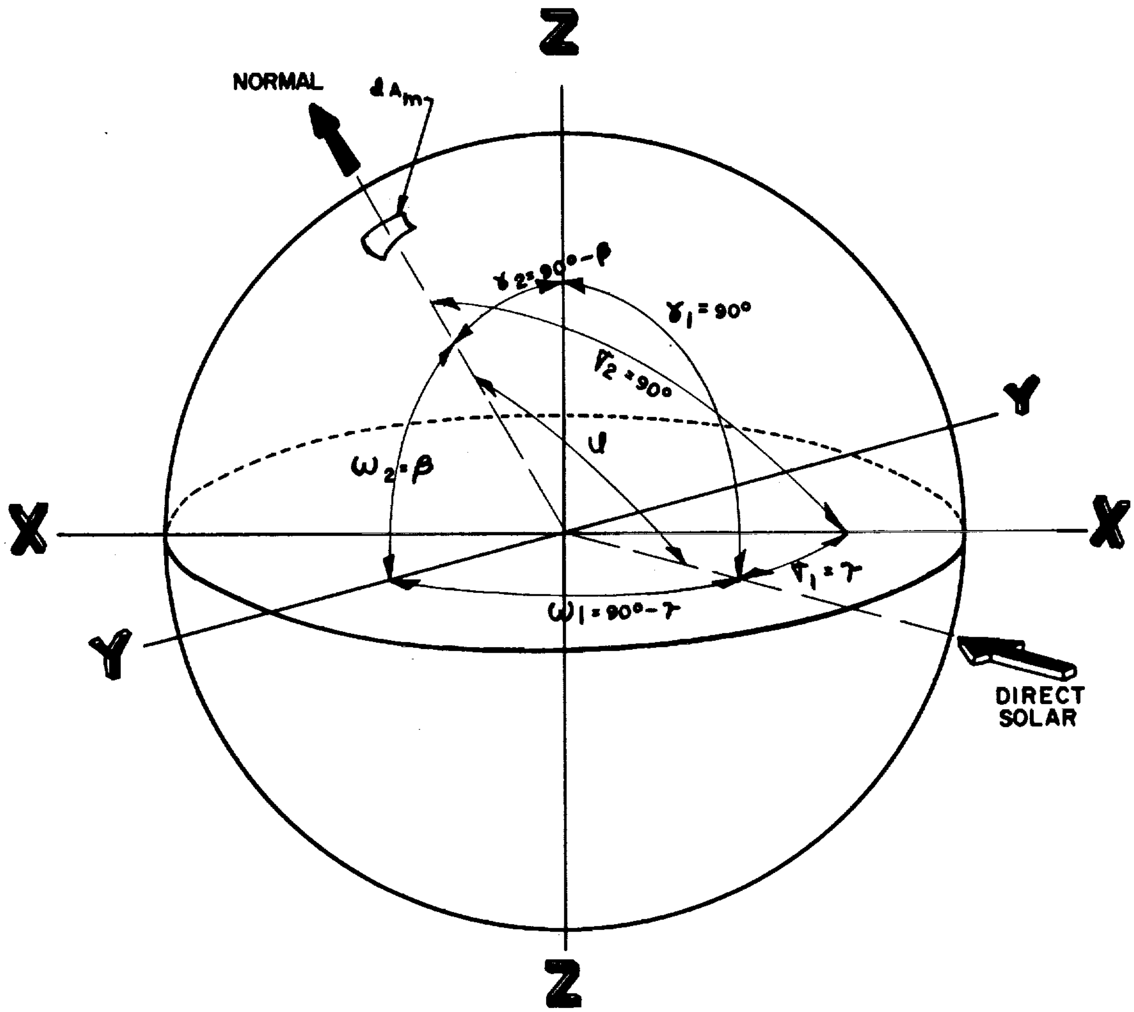

FIGURE 13. ORIENTATION OF AN ELEMENTAL AREA OF LUNAR SURFACE WITH RESPECT TO DIRECT SOLAR ENERGY

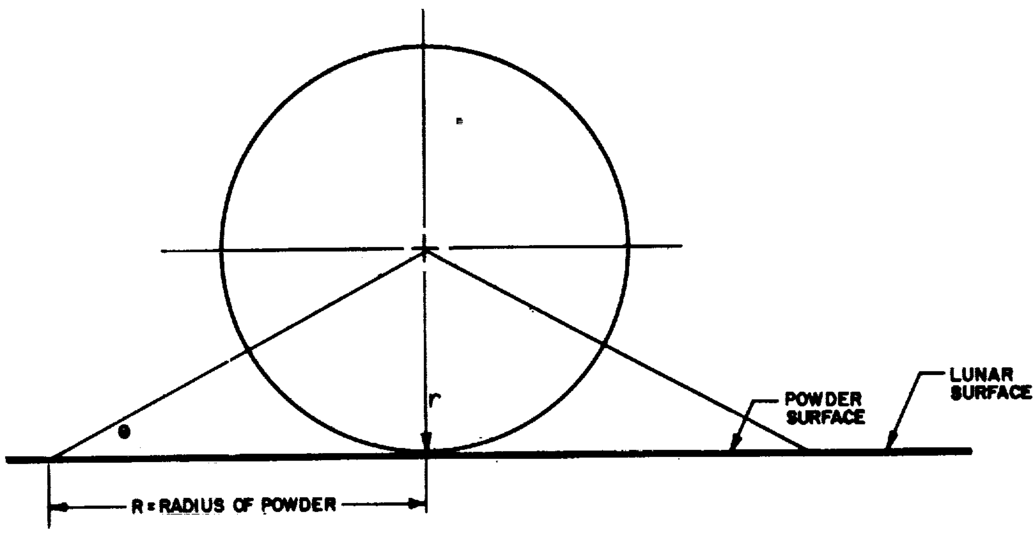

FIGURE 14. ORIENTATION OF A SPHERICAL TANK WITH RESPECT TO VARIOUS SIZE CIRCULAR AREAS OF ALTERED LUNAR SURFACE

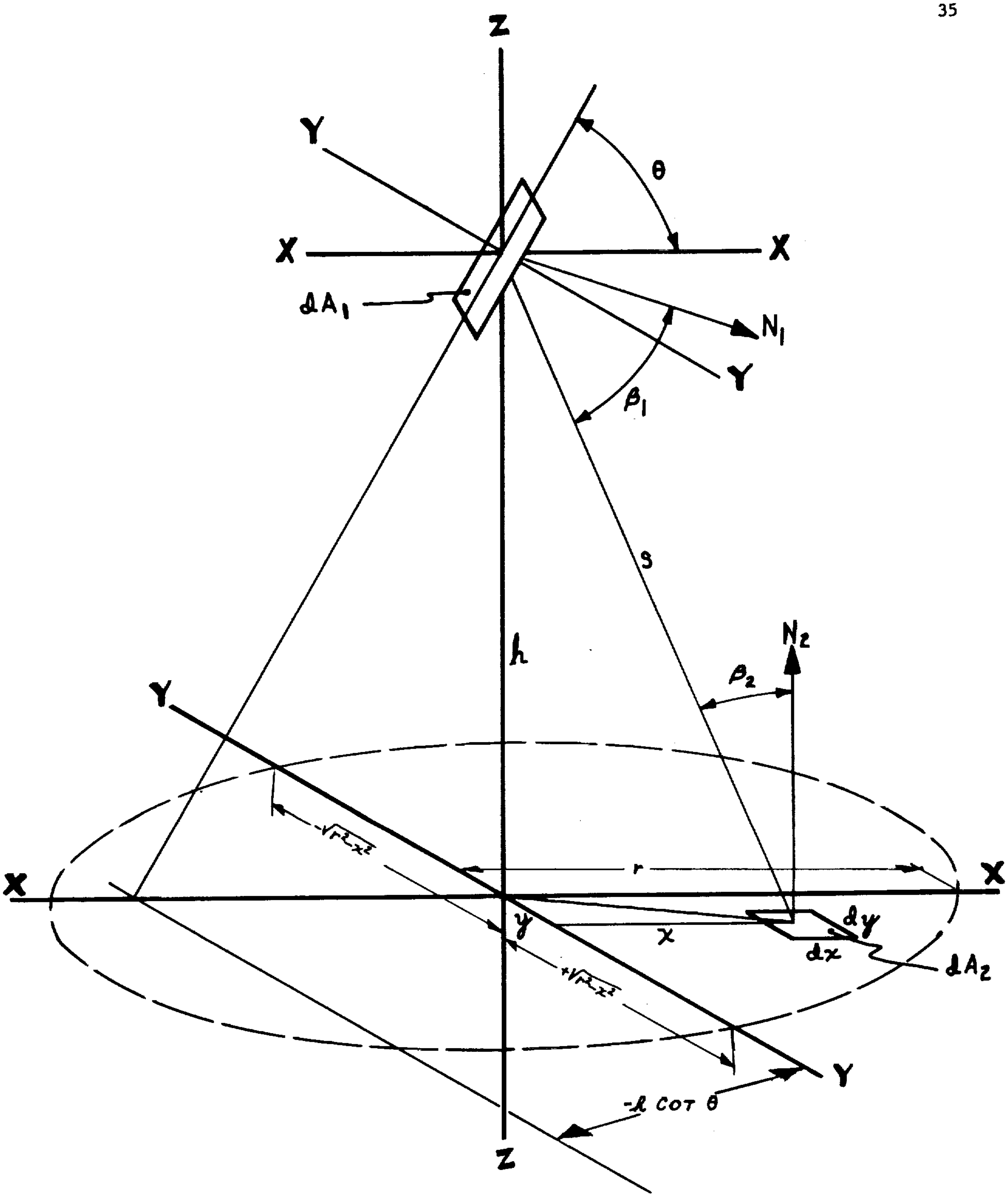

FIGURE 15. ORIENTATION OF ELEMENTAL AREA RADIATING FROM ONE SIDE TO A CIRCULAR AREA

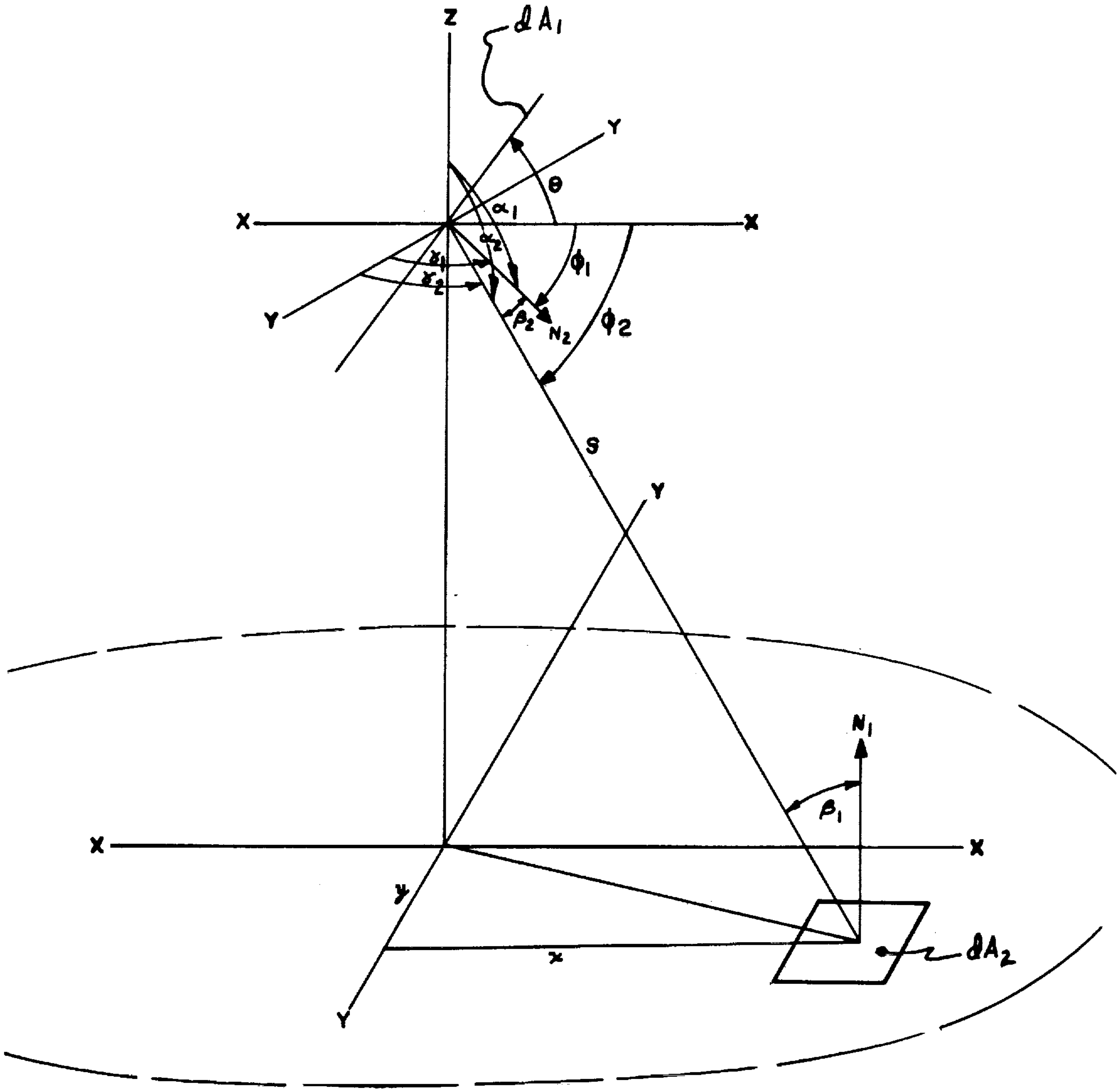

FIGURE 16. ORIENTATION OF NORMALS TO ELEMENTAL AREA AND CIRCULAR AREA WITH RESPECT TO COORDINATE AXES

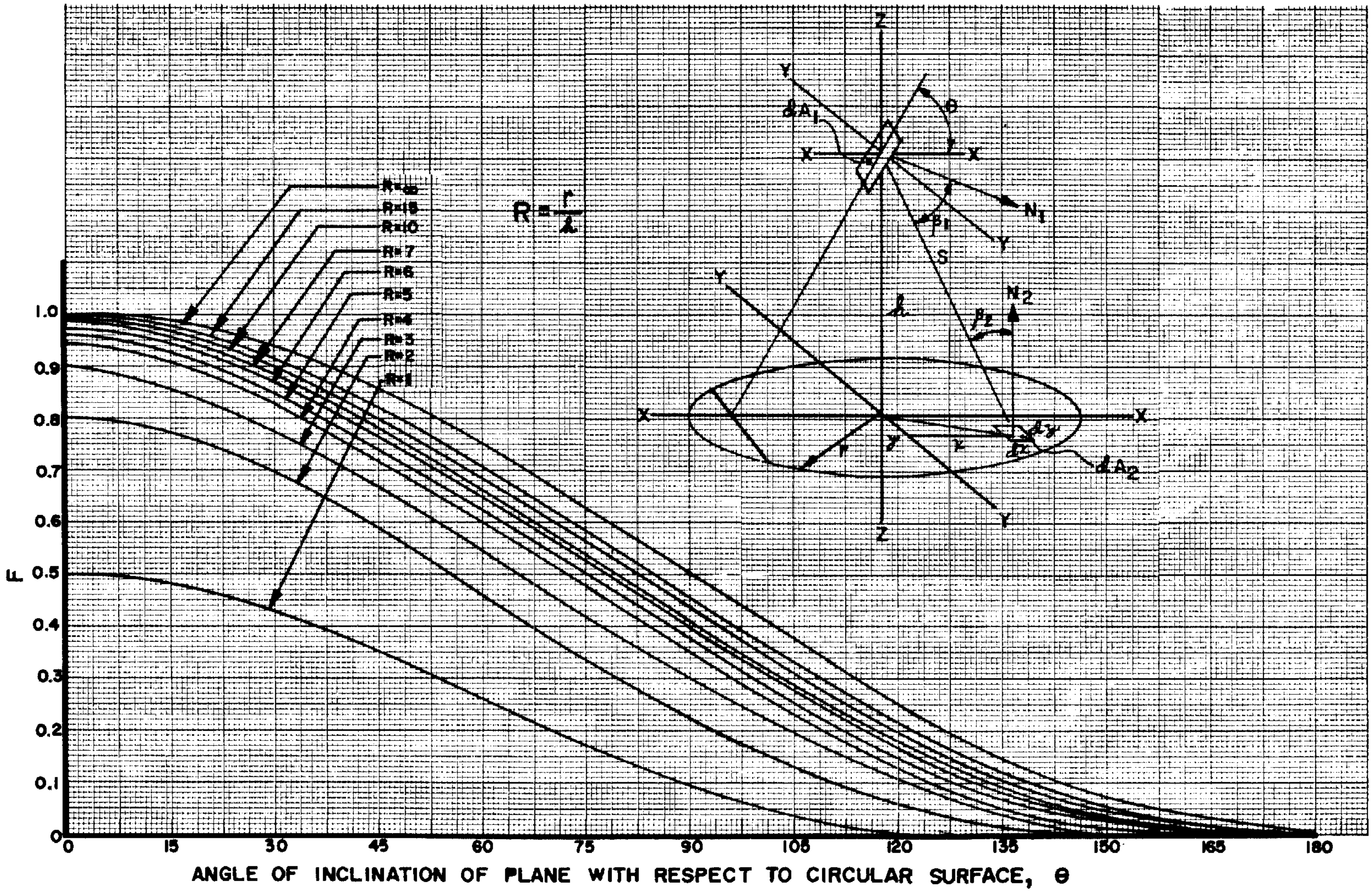

FIGURE 17. SHAPE FACTOR OF ELEMENTAL AREA INCLINED TO VARIOUS SIZE CIRCULAR AREAS VS. ANGLE OF INCLINATION

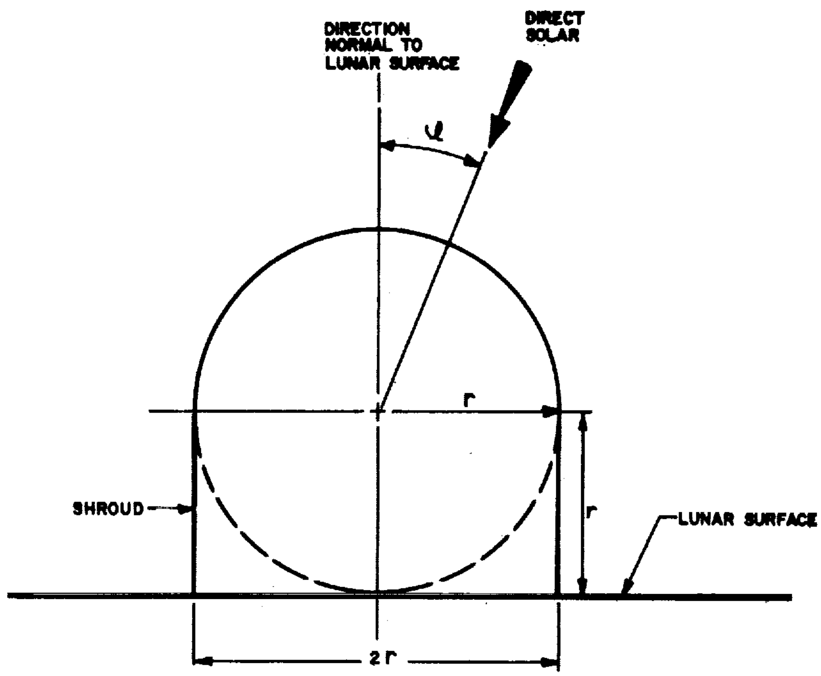

FIGURE 18. ORIENTATION OF SHROUDED SPHERICAL TANK WITH RESPECT TO DIRECT SOLAR ENERGY

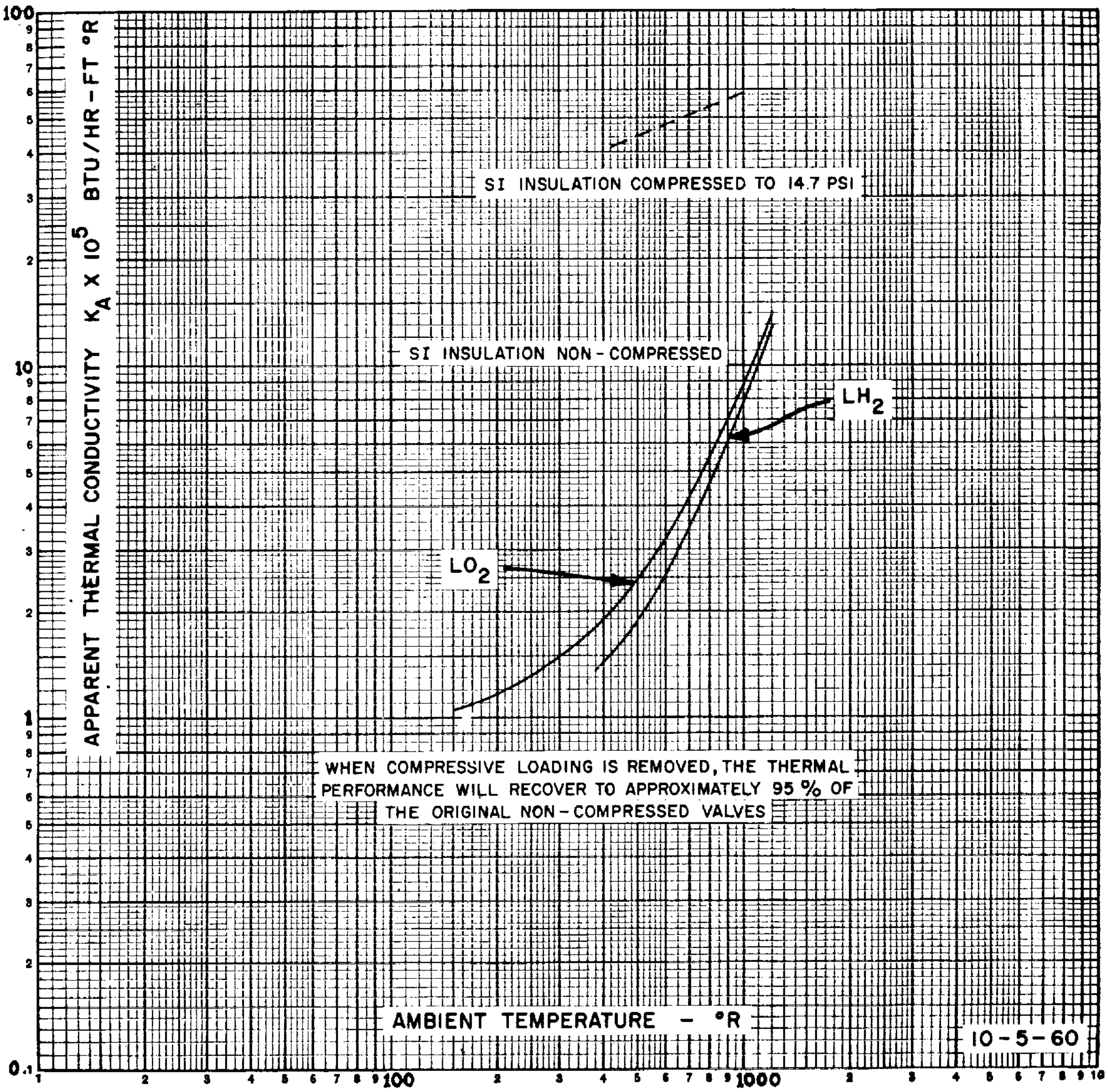

FIGURE 19. APPARENT THERMAL CONDUCTIVITY OF LINDE SI INSULATION BETWEEN VARIABLE AMBIENT TEMPERATURE & LIQUID HYDROGEN, OXYGEN (REF. 3)

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3. Olivier, J.R. and Dempster, W.E. "Orbital Storage of Liquid Hydrogen" NASA Technical Note D-559.

NASA-Langley, 1962

NASA TN D-1117
National Aeronautics and Space Administration.
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W. E. Dempster, R. L. Evans, and J. R. Olivier.
July 1962. 40p. OTS price, $1.00.
(NASA TECHNICAL NOTE D-1117)

Unlike the earth with its attendant atmosphere, the moon is situated in a near vacuum (10^{-13} earth atmospheres) which produces a thermal environment quite different from that on earth. Thus, the temperature of the lunar surface and objects located thereon depends primarily on the laws and mechanisms of radiation heat transfer. The temperature of the lunar subsurface and foreign bodies contained therein are also influenced by this form of energy transfer, but are primarily affected by conduction heat transfer. Radiation equations are set down which show that the temperature of the lunar surface during the daylight period is proportional to the cosine of the angle formed by the sun's rays and a

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